Development of a Thrust Stand Micro-Balance to Assess Micropropulsion Performance

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ABSTRACT

As proposed spacecraft and their associated thrusters have become smaller, technology has been developed to meet the demand for performance measurements for the extremely low force levels produced. For such thrusters, it is also desirable to measure the mass changes resulting from the utilization of propellant associated with either the steady state thrust or transient impulses. A thrust stand and novel data analysis method is presented to make both thrust (or impulse) and mass change measurements concurrently. It is shown that very accurate and repeatable measurements of mass can be made using an existing thrust stand system. Furthermore, it is shown that impulse and mass measurements can be resolved at the same time from a single thrust stand trace.

INTRODUCTION

A Thrust Stand micro-Mass Balance (TSMB) has been developed to accurately measure the thrust (or impulse) and change in thruster mass as a diagnostic tool for aiding in the development of new and innovative micropropulsion systems. When looking at a thruster's performance, the two most common parameters are thrust (T) and specific impulse (Isp). Numerous thrust stands [1-3] have been designed to obtain thrust measurements for relatively low steady-state forces or transient impulses. However Isp measurements can be more involved, and require knowledge of the mass flow rate, as given by the relation,

$$Isp = \frac{T}{\dot{m}\, g_o} \quad \text{or} \quad Isp = \frac{I}{\Delta m\, g_o}$$

where $\dot{m}$ is the propellant mass flow rate, Δm is the change in propellant mass, I is the total impulse, and g_o is the Earth's gravitational constant. For a thruster using a gas or liquid propellant, the mass flow rate (change in propellant mass) can often be measured using mass flow meters. However for the solid propellant system a mass flow meter typically cannot be used. One way to determine a thruster's average mass flow rate is to measure the mass before and after the thruster firing. However to time resolve the mass flow, a more sophisticated technique is required.

Most thrust stand measurements are conducted in a vacuum chamber. For solid propellant systems, a thruster would have to be weighed before and after a thruster firing on a scale outside of the chamber in order to measure the change in mass of the propellant and determine the specific impulse. The mass measurement would involve removing the thruster from the vacuum system frequently, which could cause contamination issues especially when dealing with very small changes in mass. Ideally, it would be best to measure the change in mass directly on the stand while maintaining similar conditions used during the thrust testing. It is theorized that current thrust stand technology can be adapted to measure these small changes of mass to the same degree of accuracy as a high resolution scale with the benefit of being vacuum rated.

Another benefit of developing the TSMB is to better understand the transient properties of a thruster's specific impulse. The time resolution of thrust measurements is quite good which leads to accurate total impulse. However using many current methods for solid propellant systems, changes in mass are not time resolved at all but are simply an

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14. ABSTRACT

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average over thruster operation. A system has been developed so that the mass change could be measured very accurately in time. This makes it possible to time resolve the specific impulse. Time resolved Isp information can be used in thruster design to create more efficient or tailored systems.

THRUST STAND MICRO-MASS BALANCE

The TSMB has been designed based on the nNTS [4] and NIBS [5] systems, which resolve thrust measurements from a torsion pendulum that pivots around a vertical axis of rotation. A force imparted to the stand results in a horizontal displacement of the target, which can be precisely measured using a Linear Variable Differential Transducer (LVDT). Robust techniques have been developed using these systems to perform force measurements as low as 80 nano-Newtons (steady-state) or 7 nano-Newton-seconds (impulse). By placing the LVDT core far from the center pivot and only allowing the stand to rotate small amounts, the motion of the LVDT rod can be linearized through the use of small angle approximations. Using a set of calibrated electrostatic combs[6], a known force can be applied to the stand, and the deflection of the stand can be measured. This gives a relationship between applied force and displacement of the LVDT under current conditions or a calibration. Conditions may change slightly between different setups, mountings, and chamber conditions; therefore, a calibration is done before and after every set of data collected.

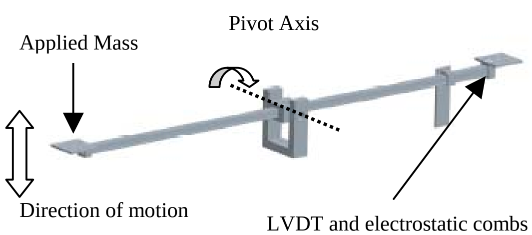


Figure 1: Schematic of the TSMB setup and configuration.

The TSMB has evolved the previous designs by rotating the stand 90° to provide a horizontal axis of rotation as shown in Figure 1. The TSMB system relies on precise mass and inertial balancing of the symmetrical arms abut the pivot axis. Changes in mass are observed as a steady-state force resulting from the imbalance of the system as propellant is exhausted. A number of other modifications have been made necessary, such as the removal of the oil baths used to provide viscous damping on the stand. In its place, an electromagnetic damping system has been adopted to provide damping of noise and braking capabilities. In addition, the electromagnetic damping system will also help to mitigate the contamination potential of the viscous oil. In consideration of all the modifications, extensive testing and enhancement of the analysis procedures has been conducted.

EXPERIMENTAL PROCEDURE

The method for resolving mass will be fully validated by using a number of different approaches, which include the use of an electrostatic calibration scheme, test masses, and testing solid propellant microthrusters. For the electrostatic calibration method, a set of charged combs is used to impart a known steady-state force, which simulates a change in mass. The calibration scheme described by Selden and Ketsdever [6] is used. Once electrostatic simulation was shown, three separate experiments were set up, each providing more insight into the TSMB's accuracy and application. First, preliminary feasibility tests were conducted using a range of known test masses, which served to proof of concept. The test masses were weighed on an external mass scale with a resolution of 10 microgram. Second, NIST calibration masses were used to achieve greater accuracy and to remove any error that the external mass scale could cause. Because the NIST masses were a known weight, the external scale and the TSMB could be compared directly against each other for accuracy and precision. Finally, the TSMB was used to measure mass change of small digital microthrusters packed with solid propellant. The microthrusters used were similar to those described by Lewis [7].

For the initial tests, two objects were chosen ranging in mass from 10 mg to 100 mg. The thrust stand micro balance was set up in a Plexiglas box so as to minimize the effects of air currents. The masses were deposited on the stand though a long tube that protruded from the box. Each mass was weighed individually by placing it on the stand in the exact same location as the electrostatic calibration combs. Great care was taken in all measurements in order to try and minimize the error that would be induced by location variance. The masses were also measured and compared with the mass measurements taken on an Ohaus model No. AP250D scale, factory calibrated and actuate to 10 micrograms.

The second set of masses used were NIST certified. A 1mg, 5mg, and 10 mg mass were used, each certified to be accurate to within 0.1% percent.

This experiment was set up in the same way as the previous one. Each mass was measured 10 times on the TSMB as well as ten times on the Ohaus scale.

The final experiment conducted was using digital microthrusters. These thrusters are packed with a solid propellant that combusts and is expelled out a small “nozzle” producing an impulse. They were mounted so that the force from the impulse and the force from the mass change were in the same direction and both could be measured using the TSMB. Two different calibrations schemes were necessary in order to analyze the two different modes of the stand. The first mode was the transient mode. From this data and calibration, the impulse of the thruster was determined as described by D’Souza and Ketsdever [5]. The second mode was the steady-state mode. By examining this stand property the change in mass was found. A total of four different thrusters were measured. The mass of each thruster was also measured before and after firing on the Ohaus scale to compare with the TSMB results.

RESULTS AND DISCUSIONS

Figure 2 shows the TSMB mass measurement results for the first set of masses tested. Each mass was weighed on the TSMB ten times and showed an average weight of $1.05x10^{-5}$ kg and $4.38x10^{-5}$ kg respectively. For each mass the standard deviation of the ten measurements was 0.44% and 0.22% respectively. The measurements from the TSMB were compared those from the Ohaus scale. The Ohaus scale measured average values of $1.10x10^{-5}$ kg and $4.26x10^{-5}$ kg for the two masses with a variation between the Ohaus scale and the TSMB of less then 5 %.

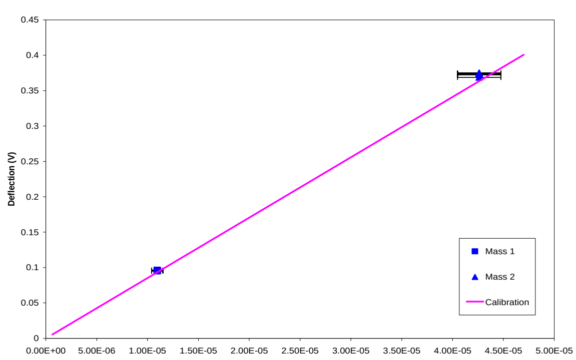


Figure 2: Plot of the known masses and the corresponding deflection of the TSMB.

Next, the NIST calibrated masses were measured numerous times on both devices. When measured on the TSMB the 1 mg, 5 mg, and 10 mg weights had an average value of $9.56x10^{-7}$ kg, $4.95x10^{-6}$ kg and $9.98x10^{-6}$ kg respectively. The percent deviations were 3.62%, 0.64%, and 0.63%, respectively. These masses were also measured on the Ohaus scale.

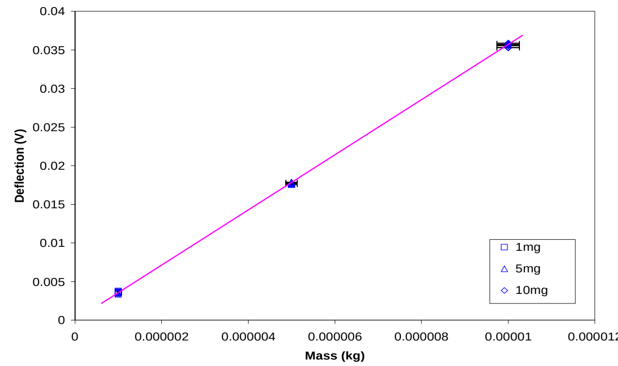
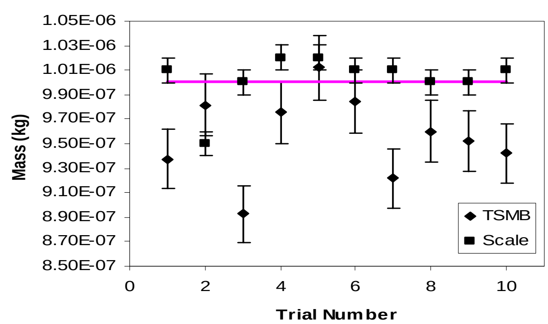
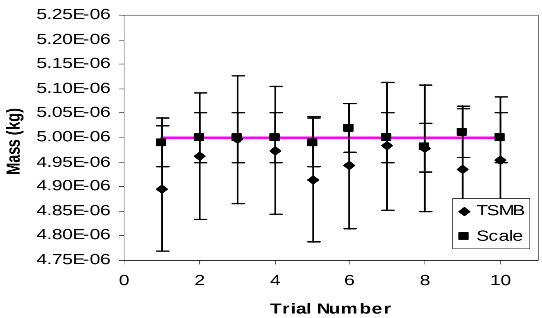


Figure 3: Plot of the NIST masses and the corresponding deflection of the TSMB.

A closer look at precision and accuracy of these two measurement devices can be seen for each individual mass in Figure 4. While the TSMB showed significant deviation for the 1 mg mass, it was less noticeable for the 10 mg mass. The major reason for this was that the 1 mg mass change is in the lower range of the TSMB’s capability for measurements in air, with a signal to noise ratio of about 40. Even with the Plexiglas enclosure the stand was still affected by the surrounding air currents. It is expected that lower mass change measurements could be obtained with higher accuracies in a vacuum chamber.



(a)



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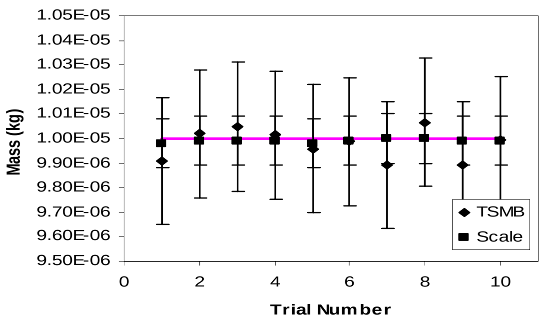

(c)

Figure 4 Ohaus scale measurements compared to TSMB measurements for the (a) 1 mg, (b) 5 mg, and (c) 10 mg NIST masses.

The final test of the TSMB system incorporated digital microthrusters. Figure 5 shows the mass loss for the four different thrusters and the corresponding calibration line for each test. For all four tests, the TSMB was able to measure the mass within a few percent.

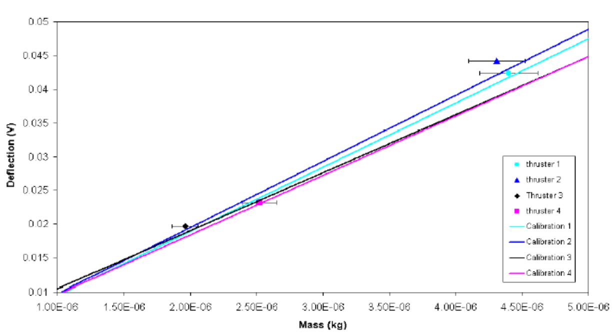

Figure 5 Mass as measured by the TSMB for 4 digital microthrusters.

When compared to the mass changes measured with the Ohaus scale the values from the TSMB are within 1.46%, 4.61%, 4.63%, and 0.46% for the four digital microthruster tests respectively. Because the thruster was not removed from the stand to measure the mass, it is an ideal method for making such a measurement. When these small thrusters are removed from the stand to be put on a convention scale, there are many opportunities for contamination as well as the possibility for un-combusted propellant to fall out leading to a less actuate measurement.

As mentioned earlier, both impulse and change in mass could be measured simultaneously from the same set of data. Figure 6 shows a typical trace of a digital microthruster firing. Using techniques describe by D'Souza and Ketsdever [5], it is possible to back out the impulse from the maximum deflection of the stand. The mass change can be determined by the difference between the steady-state deflection of the stand before and after the firing (when the TSMB returns to equilibrium). By measuring the impulse and the mass loss, the Isp can be determined.

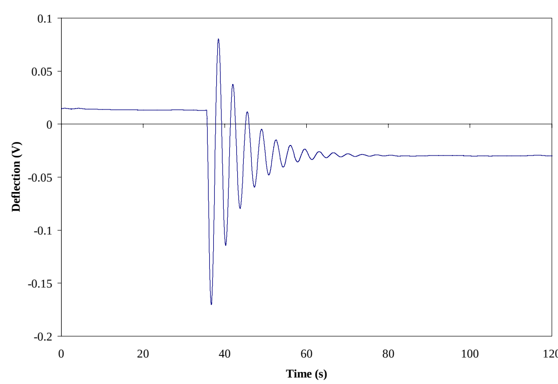

Figure 6: Typical LVDT trace of a micro thruster firing.

CONCLUSION:

In this experiment it was demonstrated that a thrust stand could be set up in a mass balance configuration so as to measure very small changes in masses; comparable with modern high-end laboratory scales. Even with the instability of in air measurements the TSMB was able to shown accuracy and precision of less then 5% for the lightest of masses. It was also shown the under the TSMB configuration, a change in mass could be found at the same time as an impulse applied from digital microthrusters. This desirable ability allow for a more accurate value of Isp to be found without the risk of contamination issues that would affect such measurements. This advance in small-scale thruster diagnostics would also allow for multiple firings without breaking vacuum. This would be extremely useful in test of such devises as arrayed digital microthrusters arrays, PPT's (pulsed plasma thrusters), colloids, FEEP's (field emission electric prolusions), and other liquid or solid propellant thrusters.

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REFERENCES

[1] E. Cubbin, J. Ziemer, E. Choueiri, R. Jahn, "Pulsed thrust measurements using laser interferometry," *Rev. Sci. Instrum.* Vol. 68, No.6, 1997, pp.2339-2346.

[2] M. Gamero-Castano, "A torsional balance for the characterization of microNewton thrusters," *Rev. Sci. Instrum.* Vol.74, No.10, 2003, pp. 4509-4514.

[3] T. Haag, "Thrust stand for pulsed plasma thrusters," *Rev. Sci. Instrum.* Vol. 68, No.5, 1997, pp. 2060-2067.

[4] A.Jamison, A.Ketsdever, and E.P.Muntz. "Gas Dynamic calibration of a nano-Newton Thrust stand," *Rev.Sci.Inst.*, Vol.73,No.10, 2002, pp.3629-3637

[5] B.D'Souza, A.Ketsdever, "Inverstigation of aLaser-Surface Interactions using a Nano-Impulse Balance," AIAA- 2004-2664, Proceedings of 35th AIAA Plasmadynamics and Lasers Conference, Portland, June 2004.

[6] N.Selden, A.Ketsdever. "Comparison of force balance calibration techniques for the nano-Newton range," *Rev.Sci.Inst.*, Vol.74,No.12, 2003, pp.5249-5254.

[7] D. H. Lewis, Jr._, S. W. Janson, R. B. Cohen*y* and E. K. Antonsson"Digital MicroPropulsion," 12*th* IEEE International Micro Electro Mechanical Systems Conference (MEMS '99), January 17-21, 1999